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EXPERIMENTAL BEHAVIOR OF CLAY MASONRY WALL WITH OPENING UNDER EFFECT OF LATERAL FORCES

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ABSTRACT

This paper presents an experimental test program, on eight clay brick masonry walls, under the effect of lateral forces. The effect of opening, boundary condition and vertical compression forces were assumed as, variables in the tests. Three of these eight tested walls were constructed which had a mid-span opening. The tested walls were designed with different supported along two, three and four edges. The top and bottom edges were assumed as simply-supported, while the vertical edges were supported by short return walls, which are restrained from rotation, so that, the two vertical edges could reasonably to be considered as rotationally fixed. The walls were loaded using a system of airbags. The ultimate strength of each wall was determined and compared with previous theoretical methods.

KEYWORDS: Brick Wall, Out of Plane Lateral Loading, Ultimate Strength & Virtual Work

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INTRODUCTION

Considerable improvements have been made, in the design and analysis methods available to calculate the capability of brick walls, that are supported on varied sides and are subject to horizontal loads, have been achieved.

The improvements, based on a virtual work, "force-based" approach still assume, failure occurs once a wall has reached its ultimate strength, and this occurs in bending at very small displacements, of the order between 2 and 5 mm, and assumes that, the moment capacity in vertical bending and diagonal bending is extended together. This restriction, whilst appropriate for wind loading, has been shown to be extremely conservative, for seismically loaded walls [1].

A common practice, to develop out of plane horizontal lateral loading, is to perform four points bending tests, implemented by Abboud et al. (1996) [2], and Galal, and Sasanian (2010) [3], on masonry panels. The load is applied in two lines, by using two steel rod's sections, but this kind of loading doesn't assist the two-way bending of testing wells. This led the studies to the concept of air mattress loading, to create a distributed uniform horizontal lateral loading, which was used in many studies, such as Griffith et al. (2007) [4]. The capacity of brick masonry walls under out of plane loading, depend on their dimensions [5], support conditions [6] and material characteristics [7]. Additionally, the presence of opening [8] and vertical pre-compression [4], also have strong influence behavior on the maximum capacity too.

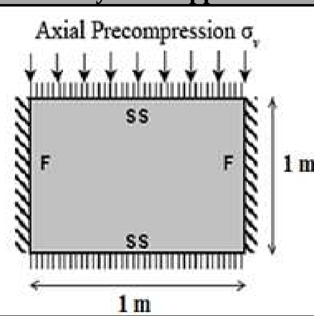
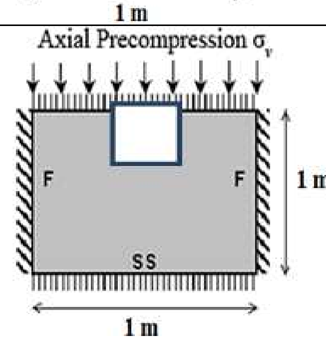
Experimental Test Program

Eight clay brick walls, subjected to static controlled horizontal laterally loading were, conducted as part of this study to investigate the load-deflection behavior, of these types of walls to their point of maximum flexural strength. The geometrical details of the tested walls are given in Table 1. It can be seen that, the tested walls consist of three groups, according to the number of supported edges. Each wall has a square panel of $1m^2$.

All tested walls in the first group were supported on all four sides; this group consists of testing walls: BW4N, BW4C, BW4NO and BW4CO. The fourth letter (C or N) in the symbol legend, refers to the presence or not of the vertical compression (0.012 MP a). The fifth letter (O) in symbol legend, refers to the symbol with opening. The second group includes the tested walls: BW3N andBW3NO, this group has a free top edge. While, the last group has: BW2C and BW2N, in this group the tested walls, which assumed support on top and bottom edges only. Return walls were constructed as a part of the first and second tested wall groups, to provide a restrained moment connection, along vertical edges. The return walls were fully connected with the half-overlap stretcher bonded type of construction.

The tested walls were constructed by seemly bricklayers, with (10) hole cored clay brick units, having a length (230) × height (76) × width (110), as nominal dimensions using half overlap stretcher bonded masonry and a typical mortar joint thickness (8-13mm), for bed and head together. The mortar mix (cement: sand) was a bucket, batched to minimize mortar batch variability. The main engineering properties of the used brick units and masonry, are listed in Table 2. All brick unit tests were conducted, in accordance with the ASTM C67 [9]. It can be seen that, the quality of these units' masonry is suitable for the used mortar mix. The compressive strength of the masonry prisms (f_{mc}), was calculated from three brick, tall prisms by compression tests, according to ASTM C1314 [10]. The flexural bond strength of this bond (f_{mt}) was determined from simple four-point bending tests on five brick tall prisms, according to ASTM E518 [11].

Table 1: Geometry of Tested Walls

<table>
<tr><th>Group</th><th>Walls</th><th>Wall Geometry and Support Conditions</th></tr>
<tr><td rowspan="4">G1</td><td>BW4N</td><td rowspan="2">
</td></tr>
<tr><td>BW4C (with Pre-compression)</td></tr>
<tr><td>BW4NO</td><td rowspan="2">
</td></tr>
<tr><td>BW4CO (with Pre-compression)</td></tr>
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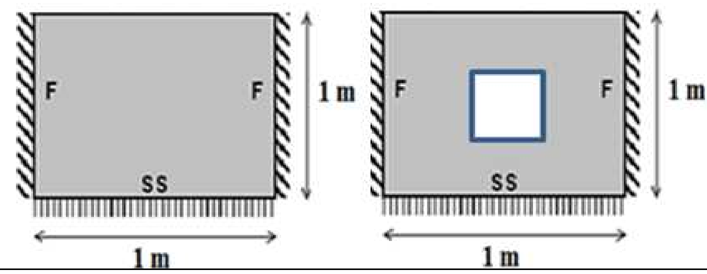
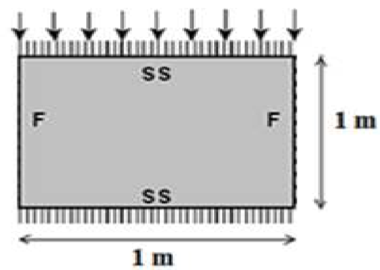
G2	BW3N	
	BW3NO	
G3	BW2N	
	BW2C (with Pre-compression)	

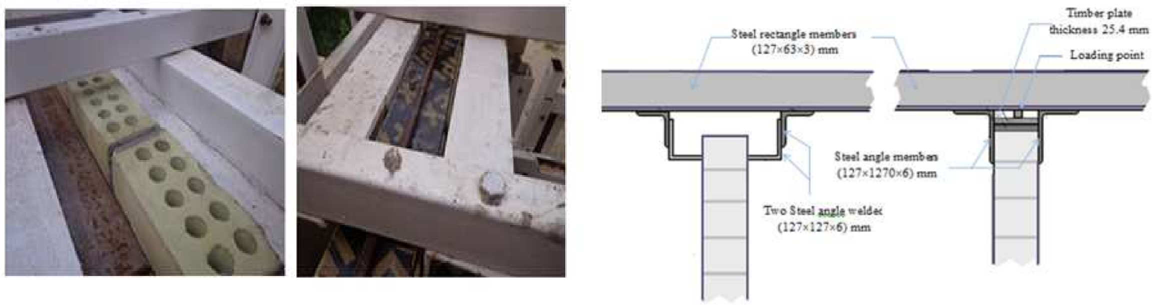
The record significant aspect of the experiment work, was the assumed method that has taken to imitate the supports, at the bottom and top edges of the tested walls, and moment restrained connection were carried out at the vertical edges. Figure 1, show the technique used to horizontally restrain the top edge of the tested walls, with and without pre-compression, which extends along the length of the top of each wall. The lateral supporting, also includes the base of each tested wall and used two angle section, to prevent sliding samples at the base, as shown in Figure 2. The free end of each return wall was restrained “clamped” and had the ability, in preventing the horizontal movement, by linking to the support framework, as shown in Figure 3.

Table 2: Material Properties

(a) Brick Unit Material Properties			
Material Parameter		**Mean**	**Co V**
Brick Tests	Compressive strength (MPa)	17.5	3.1
	Water Absorption (%)	20.6	3
	Initial Rate of section (kg/m^2/min)	0.86	0.12
(b) Masonry Material Properties(MP a)			
Wall	**Compressive Strength (f_{mc})**	**Flexural Bond Strength (f_{mt})**	
BW4N	8.9	0.43	
BW4C	11.6	0.51	
BW4NO	10.6	0.55	
BW4CO	10.2	0.48	
BW3N	11.1	0.52	
BW3NO	11.3	0.51	
BW2N	10.3	0.49	
BW2C	10.5	0.44	

Another important point that focused on these tests was, to study the effect of pre-compression loading on the flexural behavior of the brick walls. For the purpose of applying vertical pre-compression loads on the tested walls, in a manner similar to reality, three rod steel sections were positioned along the main tested wall, only without return walls. These sections were pinned at one end to a reaction frame, as shown in Figure 4, and cantilevered mode over the tested wall on its, center through a loading square pin and timber plate, used to squander the load with more uniform stress distribution, as shown in Figure 1b.

The response of the tested wall, was recorded with a number of load cells and displacement transducers. Deflections were measured, along the vertical and horizontal profiles through the mid-height and mid-length of the test wells. Lateral out of plane loads, created by the arrangement of the airbags, were transferred by load cells from the backing plywood, to a supporting reaction steel frame, before transfer to the special loading reader.



(a) Without Pre-Compression Pressure **(b) With Pre-Compression Pressure**

Figure 1: Top Edge Support

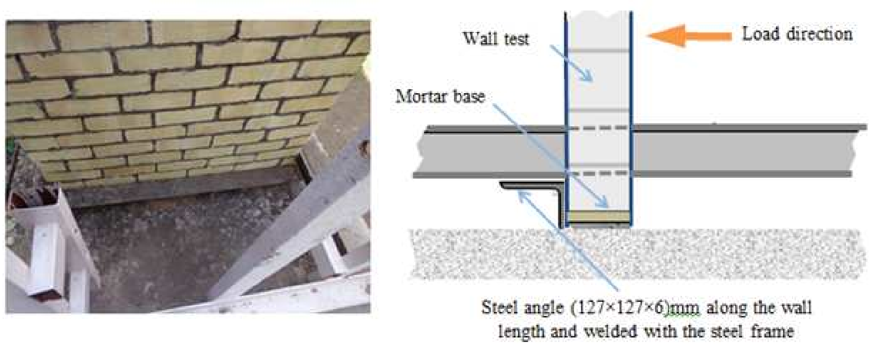


Figure 2: Bottom Edge Support

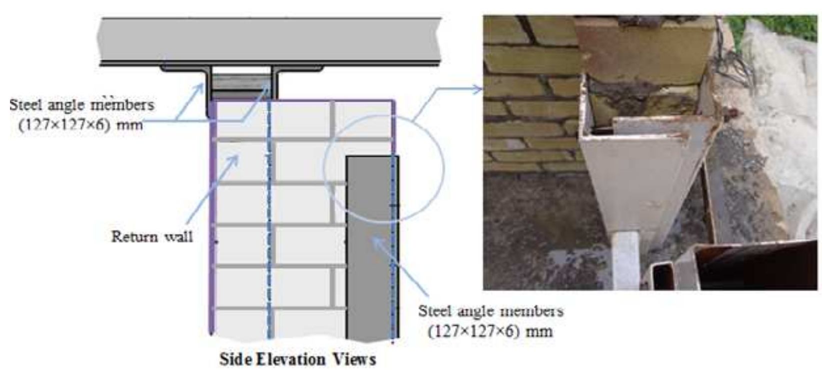


Figure 3: Vertical Edge Support

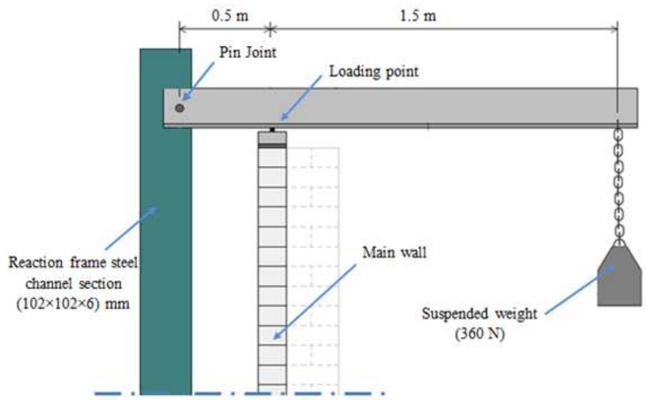


Figure 4: Vertical Pre-Compression

TEST RESULTS

The tested walls were loaded by a system of airbags, placed between the brick wall and backing plywood. The loads going into the reaction steel frame, were recorded by using four load cells and these readings divided by the net area for each tested wall and plotted to wall deflections, for all tested brick walls. The experimental results are shown, in Table 3 and Figure 5

Table 3: Experimental Results for Tested Walls

Wall	F_{ult} (kN)	W_{ult} (kPa)	Stiffness (kN/m)
BW4N	13.8	18.1	5.7
BW4C	14.5	19.1	12.4
BW4NO	9.2	13.1	4.2
BW4CO	10.0	13.9	5.25
BW3N	6.4	9.7	4.3
BW3NO	7.4	9.1	1.08
BW2N	5.8	7.6	2.2
BW2C	6.9	9.1	3.75

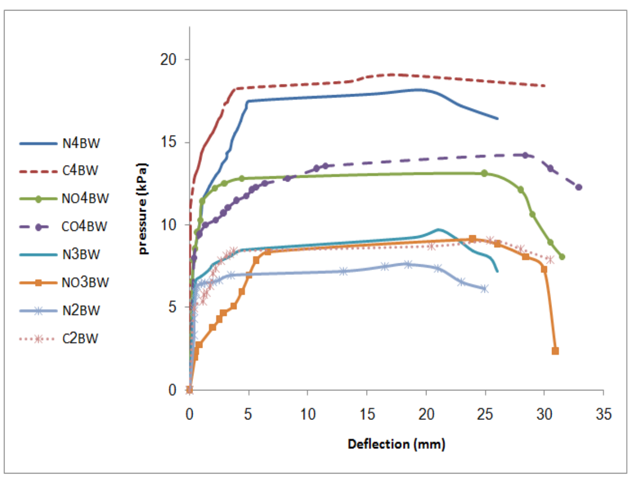


Figure 5: Load – Deflection Behavior for Tested Walls

Crack Pattern

Two Way Walls

For all tested walls, the generated patterns are synonymous, with the crack patterns typically known to occur for two-way, characterized by diagonal cracks propagating from near corners, where two neighboring supported edges intersect, as shown in Figure 6. Furthermore, diagonal cracks generally followed the natural diagonal slope of the masonry (i.e. One bed-joint cross, one prepend joint up, and so on). The differences between the idealized shapes and the observed ones, where they did occur could be attributed to factors such as, spatial variability of material properties, workmanship, and local stress concentrations, due to the approximation of the dimensions of the wall in both directions. One of the notable aspects of the crack patterns, following the initial push up to the ultimate strength of the wall is that, only a limited amount of cracking was visible at the vertical edges, and where it was present, such cracks were only partially developed. For example, walls (BW4N and BW4NO) exhibited a limited amount of cracking at the vertical edges, as shown in Figure 7. The observed cracks asymmetry is believed to be caused by the asymmetric orientation of the return walls, particularly with respect to, its inability to provide a path for the transfer of lateral load, from the main wall leaf to its vertical edges in certain instances, the occurrence of extensive cracking at the vertical edges was observed, to reduce the amount of overlapping bed area between adjacent course.

These observations indicate that, in the sequence of crack formation in two-way panels, with full moment support at the vertical edges, diagonal cracks are formed prior to vertical edge cracks, and significantly that, such panels are likely to reach their ultimate load capacity, prior to the vertical edge cracks reaching their full moment capacity. This finding has important implications toward the application of the Virtual Work method, for ultimate load capacity analysis, as the method, inherently assumes that, the moment capacity in vertical bending and diagonal bending is reached, simultaneously.

The cracking pattern of the wall BW4C is not identical, to the theoretical failure of any panel on four sides, as shown in Figure 6. This is likely, due to the proximity of the dimensions of the wall and the presence of vertical load, which prevented any initial failure, under the wall and the difficulty of growth of any diagonal cracks, which led the wall (With increased lateral load) to form cracks in a straight weak direction of the panel, which is parallel to the bed joint. As for the selection of the layer, in which the failure was due to the different quality of construction, due to the increase of lateral pressure at that point, the wall was separated into two parts. As a result of the liberation of both sections of horizontal support, each section was treated as a wall and supported only by vertical edges.

One Way Walls

A crack typically occurred at the base of the wall. In addition, all walls developed a horizontal crack at an intermediate zone, as shown in Figure 6. To the difference referred to the strength variability in different mortar joints, at the mid- height section of tested walls. And, details that, this crack passed generally through a brick-mortar interface, as observed for all tested walls. Wall cracking was often accompanied by the release of noticeable energy, as in the two way tested walls, this is evidenced by the large rush of the wall, after the failure and the wider scope because of the lack of vertical edges supported.

BW4N

BW4C

BW3N

BW3NO

BW4NO

BW4C0

BW3NL

BW3NOL

Figure 6: Cracking Pattern for Tested Walls

(a)BW4CO

(b) BW4C

(c) BW4N

Figure 7: Cracking at Return Walls in Tested Walls

Behavior of the Tested Walls BW4N and BW4C

These two solid brick walls are fortified, similarly, but variations in wall BW4C, was under pre-compression vertical pressure only. From the load-deflection relationship, as shown in Figure 8, it can be seen that, wall BW4C, with (σ_v = 0.012MPa), was stronger and stiffer than BW4N. Wall BW4C recovered a higher percentage of its maximum displacement, than wall BW4N, which perhaps was due to its vertical pre-compression pressure.

The cracking patterns for these tested walls (Figure 6), also compatibility with the typical cracking modes, have a nearly complete vertical crack lines mechanism, in one of the return walls, whereas the diagonal cracking is visible in pre-failure. This suggests that, these walls had very nearly developed, a full collapse mechanism at which, limit the strength capacity would be supposed to decrease rapidly. Due to the shorter horizontal span, this phase of response was attained at a comparatively small displacement, of about 5 mm, whereas the longer walls that were tested to the same displacements had little or vertical cracking, noted at that displacement.

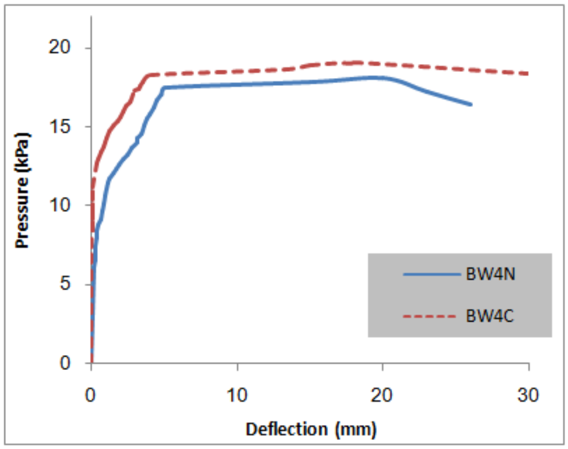


Figure 8: Load- Displacement Behavior of BW4N and BW4C

Behavior of the Tested Walls BW4NO and BW4CO

Tested walls BW4NO and BW4CO were prepared with a central opening, without and with vertical pre-compression pressure, respectively. As, with the other tested walls, both of these brick walls presented an actual amount of displacement capacity. In Addition, wall BW4CO had only a slight increase in stiffness (from 4.2 kN/mm for BW4NO to 5.25kN/mm for another wall). The increase is observed in the ultimate strength, which reaches 8%, for the pre-compression tested wall, in comparison with the other wall, as shown in Figure 9.

The cracking pattern for these tested walls, was the fully developed diagonal cracks, whereas, the vertical cracks resulting from the horizontal bending at the vertical edges was partially developed. This illustrates an important point that, at the limit, the ultimate static strength of these walls and the vertical edges has the additional ability to accept the load transfer, from the diagonal bending mechanisms.

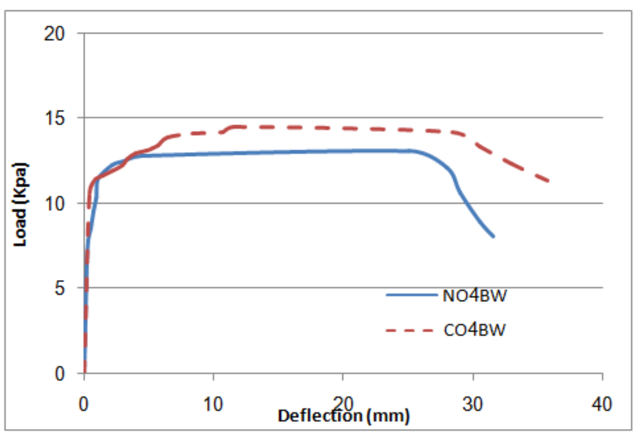


Figure 9: Load- Displacement Behavior of BW4NO and BW4CO

Behavior of the Tested Walls BW3N and BW3NO

By virtue of its free top edge, these walls had the lowest strength and stiffness, particularly compared to previous tested walls. According to its classification, as shown in Figure 10. This led to the development of diagonal cracks, especially, in the upper part of the walls at a higher rate, where the line of support is far away for any crack that occurs,

which led to the failure of the fastest. In the first loading attempt and the absence of top support and vertical loading, the wall underwent sliding between its base course and the floor, due to scanty restraint, along the bottom edges. This caused the wall to respond primarily, in one-way horizontal bending, resulting in a vertical crack along its mid-length, before rearranging behavior at final failure.

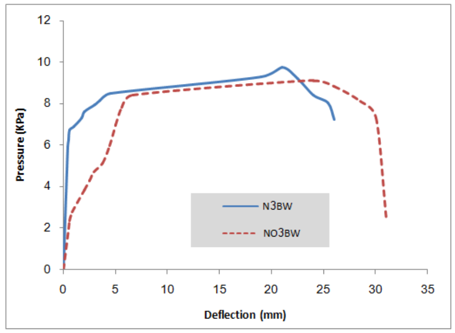


Figure 10: Load- Displacement Behavior of BW3N and BW3NO

Behavior of the Tested Walls BW2N and BW2C

The effect of pre-compression loading is not much different, in BW2N tested wall from previous cases, where the natural increase in both strength and stiffness under this effect, as shown in Figures 11. We can observe a significant increase in ultimate strength from 7.6kPa in BW2N wall to 9.1kPa in BW2C wall and by about19.7%. And increasing stiffness by about 70%, from 2.2kN/mm in BW2N, to 3.75kN/mm in BW2C

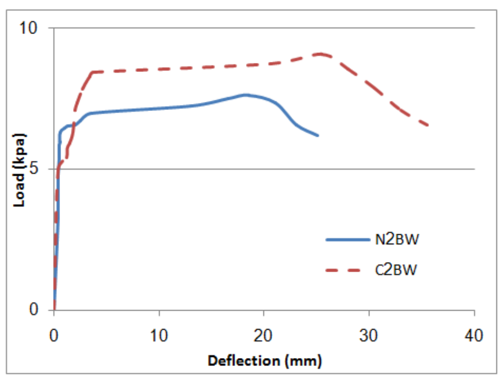


Figure 11: Load- Displacement Behavior of BW2N and BW2NO

GENERAL DISCUSSIONS

The following main observations can be made from the load-displacement relationships and failure modes. In every tested case, there is clear proof of increased stiffness and strength with present vertical pre-compression pressure, as shown by comparisons of solid walls, BW4N and BW4C (Figure 8) and tested walls, with opening BW4NO and BW4CO (Figure 9). This is mainly due to the increased torsional bed joint resistance, due to the higher vertical compressive stress on the bed joint, which participate in the moment capacity of the brick wall, in both diagonal and horizontal banding.

The walls with openings had greater strength, than the corresponding walls without openings. This inverse result is due to the truth that, the higher pressures were required, to generate the corresponding amount of external work, because the airbags worked over a reduced area along, did not affect the contribution of the longer diagonal cracks in the strength

of the solid walls (internal work).

Walls were unsupported at the top edge and exhibited less strength, and a significantly higher displacement at the limit of ultimate strength, compared with the other walls. This is due to the fact that, these walls having a longer effective span and thus requiring a greater central displacement before it could develop the full rotational capacity along its vertical edges and failure.

One of the most notable appearances of the crack patterns (Figure 6) is that, the tested walls exhibited only a limited amount of visible cracking, at the vertical edges. By contrast, the diagonal cracks were all well developed. This observation suggests that, the ultimate moment in horizontal bending, along the vertical edges of the walls is achieved at larger wall displacements, than that at which the ultimate load capacity in the wall is reached.

Analytical Predictions

Two-Way Walls

In this section, the experimental results for the tested walls are compared to the predictions of strength, obtained by applying the principles of virtual work to the idealized failure modes mechanisms (cracking patterns), shown in Figure 6. However, the virtual work method varies subtly in that, the contributions of vertical bending moment acting along the horizontal crack (yield) lines is ignored, the slope of diagonal crack lines is governed solely by the brick units geometry, and moment capacities along the vertical and diagonal crack lines are obtained, independently [12].

The underlying principles state that, the work done by the external loads, acting on the structure is converted into an equal amount of internal work or strain energy, when the brick structure deforms. In its application to laterally loaded brick panels, the external work done on the wall becomes the integral of the applied pressure, over the deflected tested wall shape (Equation 1). The internal work done by the tested wall is equal to the sum of the internal crack energies at all of the cracks, whereby, the crack energy is equal to the product of the moment, in the crack line and the rotation of the crack line along its axis (Equation 2).

$$\delta U_{ext} = W \int \delta\Delta . dA \ (exernal\ work) \quad 1$$

$$\delta U_{int} = \sum M_i \delta\theta_i (internal\ work) \quad 2$$

Equating the external work with the internal work, enables solution for the load resistance of the wall (w), as a function of the moment resistance at each crack line (M_i) and the displacements (Δ) and rotations (θ), along the wall, which are in turn defined by the failure mechanism. M_i is the total moment resistance, over the full length of the crack. The expression used to predict the bending strength of walls [13, 14]:

$$W = \frac{2a_f}{L^2}(K_1 M_h + K_2 M_d) \quad 3$$

Where a_f, k_1 and k_2 are coefficients, based on the wall geometry and boundary conditions, L is the effective length of the wall, and M_h and M_d are the horizontal and diagonal bending moment capacity of the masonry wall, per unit length of crack line.

According to the AS 3700 [13], the expressions for the respective moment capacities are taken as follows:

$$M_h = \emptyset . k_p . (0.44 \, f_{ut} + 0.56 \, f_{mt}). Z_d \tag{4a}$$

$$M_h = (2)\emptyset . k_p \sqrt{f_{mt}} \left(1 + \frac{f_d}{f_{mt}}\right). Z_d \leq (4)\emptyset . k_p \sqrt{f_{mt}} . Z_d \tag{4b}$$

$$M_d = \emptyset . f_t . Z_t \tag{5}$$

Where, M_h is taking the minimum value from these equations, $f_t = 2.25\sqrt{f_{mt}}$ Is the equivalent flexural strength of the masonry, along a diagonal crack line, expressed in terms of the masonry tensile bond strength format and the effective section modulus of the masonry, along a diagonal crack Z_t. f_d is the vertical compressive stress in the wall, at its mid-height, which includes the vertical pre-compression, applied at the top of a wall. In subsequent calculations, mean values were used for the material properties and values of 1 were assigned to the capacity reduction factor, φ and prepend factor KP.

Willis et al., 2004 [14], an alternative expression was proposed for the moment capacity of masonry wall in horizontal and diagonal bending. These are reproduced as Equations 4 and 5, respectively, in a moment per unit length of crack formulation.

$$M_h = \frac{1}{h_u + t_j}\left[0.5 \, \tau_u k_b (l_u + t_j). t_u^2\right] \tag{6a}$$

$$M_h = \frac{1}{2(h_u + t_j)}\left[(f_{ut} - v . f_d). h_u \frac{t_u^2}{6}\right] \tag{6b}$$

$$M_d = \frac{sin\varphi}{h_u + t_j}\left[0.5(sin\varphi)^3 \tau_u k_b (l_u + t_j) t_u^2 + (cos\varphi)^3 (f_{mt} + f_d) \frac{0.5(l_u + t_j) t_u^2}{6}\right] \tag{7}$$

where τ_u , is the ultimate shear bond stress of a bed joint given as τ_u=1.6 f_{mt}+0.9 f_d, φ, is the slope of a diagonal crack line, which can be determined from unit geometry, v is the Poisson's ratio of the masonry, typically taken as 0.2[15], k_b, is a numerical factor, used to calculate the shear stress, due to torque on a rectangular cross section [16] and is equal to 0.214, for the masonry units used in these walls. l_u, t_u and h_u is the length, height and width of the unit brick, respectively. While t_j is the mortar thickness.

Table 4, lists the results of the experimental and analytical calculations. The mean values for W_{pred}/W_{exp} were essentially the same, for the Australian code and Willis expressions, i.e. 1.03 and 0.98, respectively.

Table 4: Analytical Results of the Virtual Work Approach

Wall	Experimental	AS 3700 Expression		Willis Expressions	
	W_{exp} (kPa)	W_{pred} (kPa)	W_{pred}/W_{exp}	W_{pred} (kPa)	W_{pred}/W_{exp}
BW4N	18.1	19.64	1.08	18.04	0.99
BW4C	19.1	21.5	1.12	19.3	0.98
BW4NO	13.1	13.8	0.94	13.08	0.99
BW4CO	13.9	14.4	1.04	13.3	0.96
BW3N	9.7	12.87	1.32	11.29	1.16
BW3NO	9.1	7.94	0.87	7.42	0.81
		Mean Value	1.03	Mean Value	0.98

One-Way Walls

Maximum bond tensile stress in the cross section of the wall, can be obtained by using basic mechanics, assuming elastic behavior and homogenized, during section properties:

$$\sigma^t(x) = \frac{w.h.x - w.x^2}{t^2} - \frac{(h-x)m_o g - V}{t} \quad 8$$

Where, h is wall height, t is the wall thickness, $m_o g$ is the weight and V is the compression force on the wall. w is the uniformly applied wall cracking load, and the value of this force is calculated, by assuming the maximum tensile stress to be equal to the brick masonry bond strength, i.e. $\sigma T(x) = f tm$, in Equation 8. This calculation assumes that, the brick masonry bond strength is constant with the wall height. So, w can be found directly in AS 3900 [13], as following:

$$w = \frac{8\,(f_{mt} + f_d).Z_t}{h^2} \quad 9$$

Another study, by Sorrentino et al. (2008) [17], "un cracked section analysis" has assumed an alternative assumption. The acceptable solution for (w) is assumed:

$$w = \frac{f_{tm} + \frac{V}{t} + 0.5 m_o g \frac{h}{t} + \sqrt{(f_{tm} + \frac{V}{t})(f_{tm} + m_o g \frac{h}{t})}}{1.5\left(\frac{h}{t}\right)^2} \quad 10$$

Table 5, lists the results of the experimental and analytical calculations. The mean values for W_{pred}/W_{exp} were essentially the same for the Australian code and Sorrentino expressions, i.e. 0.98 and 0.97, respectively.

Table 5: Analytical Results of the One- Way Walls

Wall	Experimental Test Results	Un crack Section Analysis		AS 3700 Expressions	
	W_{exp} (kN/m)	W_{pred} (kN/m)	W_{pred}/W_{exp}	W_{pred} (kN/m)	W_{pred}/W_{exp}
BW2N	7.6	7.93	1.04	8.03	1.06
BW2C	9.1	8.15	0.90	8.24	0.91
		Mean Value	0.97	Mean Value	0.98

CONCLUSIONS

Static airbag tests, conducted on eight clay brick masonry walls were described in this paper. The experimental data indicates that, face loaded brick walls have some ductility and a substantial displacement capacity, beyond the cracking displacement. The generated patterns are synonymous with the crack patterns, typically known to occur for two-

way, characterized by diagonal cracks, propagating from near corners, where two neighboring supported edges intersect. Furthermore, diagonal cracks generally followed the natural diagonal slope of the masonry (i.e. one bed-joint across, one perpend joint up, and so on). Finally, the results compared with the simplified expressions, for diagonal and horizontal moment capacity in walls, have been shown to give reasonably accurate predictions of wall strength. However, these expressions require further investigation, through comparisons with the experimental results of other researchers.

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